AD-A154 647

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE

(3)

REPORT DOCUMENTATION PAGE

1a. REPORT SECURITY CLASSIFICATION: Unclassified	1b. RESTRICTIVE MARKINGS
2a. SECURITY CLASSIFICATION AUTHORITY: Unclassified	3. DISTRIBUTION/AVAILABILITY OF REPORT: Unlimited. Approved for public release; distribution unlimited.
2b. DECLASSIFICATION/DOWNGRADING SCHEDULE: Never been upgraded	
4. PERFORMING ORGANIZATION REPORT NUMBER(S): ANNUAL TECHNICAL REPORT	5. MONITORING ORGANIZATION REPORT NUMBER(S): AFOSR-TR- 85-0392
6a. NAME OF PERFORMING ORGANIZATION: UNIVERSITY OF CALIFORNIA — 6b. OFFICE SYMBOL (If applicable): Davis	7a. NAME OF MONITORING ORGANIZATION: AFOSR/NE
6c. ADDRESS (City, State and ZIP Code): Division of Materials Sc and Engineering, Dept. of Mechanical Engr., Univ. of California, Davis, CA 95616	7b. ADDRESS (City, State and ZIP Code): Bolling Air Force Base, Building 410, D.C. 20332
8a. NAME OF FUNDING/SPONSORING ORGANIZATION: Air Force Office for Scientic Research — 8b. OFFICE SYMBOL (If applicable): AFOSR/NE	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER: Contract number AFOSR-82-0081
8c. ADDRESS (City, State and ZIP Code): Bolling Air Force Base, Building 410, D.C. 20332	10. SOURCE OF FUNDING NOS.

PROGRAM ELEMENT NO.	PROJECT NO.	TASK NO.	WORK UNIT NO.
6-1102F	2306/A1		

DTIC ELECTE JUN 4 1985 B

11. TITLE (Include Security Classification) Fundamental Investigations of Failure During Superplastic Forming Process

12. PERSONAL AUTHOR(S) Benjamin Hidalgo-Prada and Amiya K. Mukherjee

13a. TYPE OF REPORT	13b. TIME COVERED	14. DATE OF REPORT (Yr., Mo., Day)	15. PAGE COUNT
ANNUAL TECHNICAL	FROM 2/1/84 TO 1/31/85	1985/3/12	16

16. SUPPLEMENTARY NOTATION

To be published in the Proceedings of International Conference on Strength of Metals and Alloys, Montreal, Canada.

17. COSATI CODES			18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
FIELD	GROUP	SUB. GR.	Superplasticity, Titanium Alloys, Mechanical behavior, Deformation mechanisms.

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

The effects of strain rate on the stress-strain behavior of Ni-modified Ti-6Al-4V (Ti-6Al-4V-2Ni) at superplastic forming temperature (815°C), were investigated. The microstructural evolution during superplastic deformation (SPD), produced strain hardening at low strain-rates and strain softening at high strain rates. Maximum attainable superplastic ductility, observed at intermediate strain rates, was associated with a dynamic balance between strain hardening and softening. Metallographic evidence is presented to show that the observed strain hardening is due to deformation-enhanced grain growth in the α and β phases, while the strain softening can be attributed, primarily, to grain size refinement, due to dynamic recrystallization.

Additional keywords: titanium alloys, alpha beta

DTIC FILE COPY

20. DISTRIBUTION/AVAILABILITY OF ABSTRACT: UNCLASSIFIED/UNLIMITED ☒ SAME AS RPT. ☐ DTIC USERS ☐	21. ABSTRACT SECURITY CLASSIFICATION: Unclassified

22a. NAME OF RESPONSIBLE INDIVIDUAL	22b. TELEPHONE NUMBER (Include Area Code)	22c. OFFICE SYMBOL
Dr. Ivan Caplan, Dr. Alan Rosenstein	202-767-4933	AFOSR/NE

DD FORM 1473, 83 APR — EDITION OF 1 JAN 73 IS OBSOLETE.

85 04 22 142

SECURITY CLASSIFICATION OF THIS PAGE

ANNUAL PROGRESS REPORT
AFOSR GRANT NO. AFOSR-82-0081
(Period 2/1/84 to 1/31/85)

FUNDAMENTAL INVESTIGATIONS OF FAILURE DURING SUPERPLASTIC FORMING PROCESS

by

A. K. Mukherjee and B. Hidalgo-Prada

Division of Materials Science and Engineering
Department of Mechanical Engineering
University of California
Davis, California 95616

Submitted to

Dr. Ivan Caplan
Dr. Alan Rosenstein
AFOSR/NE
Building 410
Bolling Air Force Base
D.C. 20332

March 1985

CORRELATION BETWEEN MECHANICAL PROPERTIES AND MICROSTRUCTURE IN A Ni-MODIFIED SUPERPLASTIC Ti-6Al-4V ALLOY

B. Hidalgo-Prada and A. K. Mukherjee

Division of Materials Science and Engineering, Dept. of Mechanical Engineering, University of California, Davis, CA 95616, USA

SUMMARY

The superplastic deformation (SPD) properties of Ti-6Al-4V modified by the addition of 2 percent Ni (Ti-6Al-4V-2Ni) have been investigated in the temperature range between 750-870°C and strain rates from 10^{-5} - 10^{-2} s^{-1}. It was found that the effect of microstructural changes occuring during SPD produced strain hardening and strain softening. Metallographic evidence is presented to show that the observed strain hardening is due to deformation-enhanced grain growth of both α and β phases. The strain softening was primarily due to grain size refinement. Maximum attainable super-plastic ductility was found to be associated with a dynamic balance between strain hardening and softening. Wedging and pinching off of the α-grains by the more diffusable β-phase through grain boundary diffusion seems to be an important mechanism in the deformation process of the Ni-modified Ti-alloy in the superplastic temperature and strain-rate range studied.

1. INTRODUCTION

Many titanium alloys exhibit superplastic deformation behavior in the temperature range where the α and β phases co-exist. Ti-6Al-4V, the most commonly used Ti alloy, is superplastic at temperatures between 850°C and

950°C, with optimum superplastic properties attained near 925°C [1], the temperature frequently used for superplastic forming (SPF) operations with this alloy. However, lower SPF temperatures would be desirable to reduce oxidation problems, shorten forming cycle times, and reduce die costs. Thus, there is technological interest in lowering the forming temperature of Ti-6Al-4V by addition of a suitable β-stabilizer. Furthermore, alloy additions with high diffusivities can accelerate creep rates, allowing the creep process essential to superplastic deformation to proceed at reasonable rates below the conventional SPF temperatures for the base alloy. Alloy additions of β-stabilizers such as Ni, Fe, Co, that diffuse rapidly in Ti, have been found to lower the optimum SPF temperature of Ti-6Al-4V alloy [2,3]. Among these, Ti-6Al-4V alloy modified by the addition of 2 percent Ni (Ti-6Al-4V-2Ni) appears to possess the best potential in lowering the SPF temperature without sacrificing the ease of its formability. This progress report describes the work carried out to analyze the superplastic deformation properties of the Ni-modified Ti-6Al-4V alloy at SPF temperature and to correlate them to the microstructure. Furthermore, the mechanisms responsible for the observed stress-strain behavior in the Ti-6Al-4V-2Ni alloy and their correlation with the microstructural evolution produced by the deformation, are detailed.

2. EXPERIMENTAL PROCEDURES

The Ti-6Al-4V-2Ni alloy used in this investigation had a nominal composition (wt percent) of 5.78 Al, 0.08 Fe, 0.01 Co, 2.10 Ni and balance Ti. Original 7 kg ingots of the Ni-modified alloy (cast by TIMET) were broken down in the conventional manner, and finish-rolled in the α+β phase field to produce a fine mixture of equiaxed α and β grains. The final material was received as a

sheet with thickness of approx. 1.3 mm, from which test specimens with tensile axis parallel to the rolling direction were machined. To optimize the initial microsturcture, tensile samples were annealed in purified argon atmosphere for 1 hour at 815°C.

Uniaxial tensile tests were conducted using an MTS servohydraulic machine interfaced with a PDP/11 computer and fast digital data acquisition system. A Quad Elliptical Radiant heating furnace provided a heating rate of 200°C/min, with a phaser power controller which maintained stable temperatures to within ±1°C. All tests were conducted in a purified argon atmosphere. Upon completion of the tests, specimens were quenched under load in pre-chilled argon. Samples were held at the test temperature for 20 minutes before testing.

To determine the SPD behavior pertinent to this investigation, two types of high temperature tests were conducted: 1) Continuous tensile tests to ascertain the effect of rate of deformation on the microstructural evolution, at constant temperature and for different strain levels up to fracture. 2) To minimize the effect of microstructural changes observed during SPD of the Ni-modified alloy, tensile specimens were pre-strained at temperature of 815°C and strain rate of 2×10^{-4} s^{-1} up to a total true strain of 0.20.

Samples from deformed specimens were investigated by scanning (SEM) as well as by transmission (TEM) electron microscopy.

3. RESULTS AND DISCUSSION

It has been determined that a large volume fraction of the β-phase in α-β titanium alloys, is essential to SPD [1]. Furthermore, it has been found that equal volume fraction of the two phases in a duplex alloy, produces optimum superplastic properties [4]. The static annealing of the Ni-modified (α+β) Ti

at 815°C for 1 hour, (SA-1-815) produced volume fractions of the α-phase (f_v) and β-phase (f_v) approximately 1:1 (49 percent β). In addition, this heat treatment also yielded very similar phase sizes (λ^{α} = 6.3 μm, λ^{β} = 5.7 μm). The main purpose of the annealing program was to obtain a suitable and similar initial microsturcture for the tensile tests. Furthermore, contrary to earlier belief, it has been determined in previous work [5] as well as in the present investigation, that the microstructures of the base and Ni-modified alloys undergo substantial evolution during SPD. Thus, the concept of constant microstructure during deformation for this alloy becomes irrelevant. Instead, optimization of the initial microstructure for superplasticity is more desirable.

The temperature and strain rates selected for deformation in this investigation were such that the specimens deformed in region II of superplasticity. The results illustrated in Fig. 1, show the effect of the rate of deformation on the SPD behavior on the Ni-modified alloy. These test were conducted at high, intermediate and low strain rates (5×10^{-3}, 2×10^{-4}, 5×10^{-5} s^{-1}) for the optimum temperature of 815°C and up to true strain of 1.0. Fig. 1 also illustrates the processes of strain hardening and strain softening occurring during deformation. The strain softening observed at high strain rate (5.0×10^{-3} s^{-1}), was primarily due to grain refinement of both α and β phases, as illustrated in Fig. 2. This process of grain refinement during SPD is due to dynamic recrystallization, which produces fine equiaxed new grains replacing the large grains. At low strain rates (5.0×10^{-5} s^{-1}), significant strain hardening effect was observed, as shown in Fig. 1. Microstructural correlation is presented in figure 3, where the grain growth produced by static annealing for the same time

(specimen shoulder), is contrasted with the strain-enhanced grain growth at the specimen gauge length. It can be seen that for test conditions leading to strain hardening, there is deformation-enhanced growth of both α (dark) and β (light) phases. In the absence of overt cavitation, the maximum attainable superplastic ductility was associated with a dynamic balance between strain hardening (due to grain growth) and strain softening (due to recrystallization). This behavior was observed at intermediate strain rate (2.0×10^{-4} s^{-1}) as illustrated in Fig. 1. The evolution of the microstructure resulting from dynamic balance conditions can be detailed from Fig. 4. This micrograph illutrates the fact that at superplastic forming temperature and intermediate strain rates, there appears to be a rapid deformation-enhanced distribution of the softer phase β, which injects itself between grains of the harder phase α. Furthermore, there is no significant change in the shape and size of the α-phase, suggesting an effective balance between phase growth-induced strain hardening and phase refinement-produced strain softening.

For further characterization of the stress dependence of superplastic strain-rate, the true activation energy was calculated from pre-strained test samples deformed at constant strain rates of 2.0×10^{-4} and 5.0×10^{-4} s^{-1} and variable temperatures. Narrow temperature increments between 780°C (1053K) and 880°C (1153K) were used, to allow some degree of microstructural stability at each temperature and flow stress level. Furthermore, pre-strained specimens were used to obtain an activation energy value consistent with some degree of steady-state condition, with regard to the observed microstructural evolution. The average value of the true activation energy, Q_T, was found to be 145 KJ/mole. The activation energy for lattice

self-diffusion Q_v, for the β-phase in Ti, obtained from radioactive ^{44}Ti tracer, have been found to be [6] about 248 KJ/mole. Thus, considering the activation energy for grain boundary diffusion, $Q_{GB} \approx 0.6\ Q_v$, we obtain $Q_{GB}(\beta\text{-Ti}) \approx 149$ KJ/mole, which is in good agreement with the $Q_T \approx 145$ KJ/mole determined. Hence, it appears that the true activation energy for SPD in the Ni-modified Ti alloy, is similar to that of grain boundary diffusion, in agreement with the interphase boundary accommodation process detailed below.

Previous investigations [2] on the mechanism for SPD in Ti-6Al-4V-2Ni, have suggested that the flow stress-strain rate behavior of each phase could be represented by the Ashby-Verrall model [7]. Our microstructural correlations of SPD behavior in the range of temperatures and strain-rates tested suggest otherwise. It appears that the controlling deformation process is that of interphase accomodation in agreement with the Spingarn-Nix model for deformation in two phase materials by diffusion creep [8]. As shown in Fig. 5, there is an apparent wedging and pinching off of the harder phase α by the more diffusible β-phase during the accomodation process. Furthermore, as predicted by the model, the interphase boundaries -- appear to be curved -- concave in the more diffusive β-phase, and convex in the harder phase α.

CONCLUSIONS

The superplastic deformation of Ti-6Al-4V-2Ni alloy deformed in region II showed strain hardening at low strain rates and strain softening at higher strain rates. The strain softening is primarily due to dynamic grain refinement. The strain hardening is due to deformation enhanced grain growth. Maximum attainable superplastic ductility was associated with a dynamic balance between hardening and softening behavior. The rate controlling deformation mechanism in this alloy appears to be that of

interphase accommodation, in agreement with the Spingarn-Nix model for deformation in the two phase microstructure by diffusion creep.

REFERENCES

1. N. E. Paton and C. H. Hamilton, Met. Trans., 10A, 241 (1979).

2. J. A. Wert and N. E. Paton, Met. Trans., 14A, 2535 (1983).

3. J. R. Leader, D. F. Neal and C. Hammond, Submitted for publication (1984).

4. D.M.R. Taplin and T. Chandra, J. Mat. Sci., 10, 1642 (1975).

5. G. Gurewitz, Ph.D. Thesis, University of California at Davis (1983).

6. J. F. Murdock, et al., Acta Metall., 12, 1033 (1964).

7. M. F. Ashby and R. A. Verrall, Acta Met., 21, 149 (1973).

8. J. R. Spingarn and W. D. Nix, Acta Met., 26, 13 (1978).

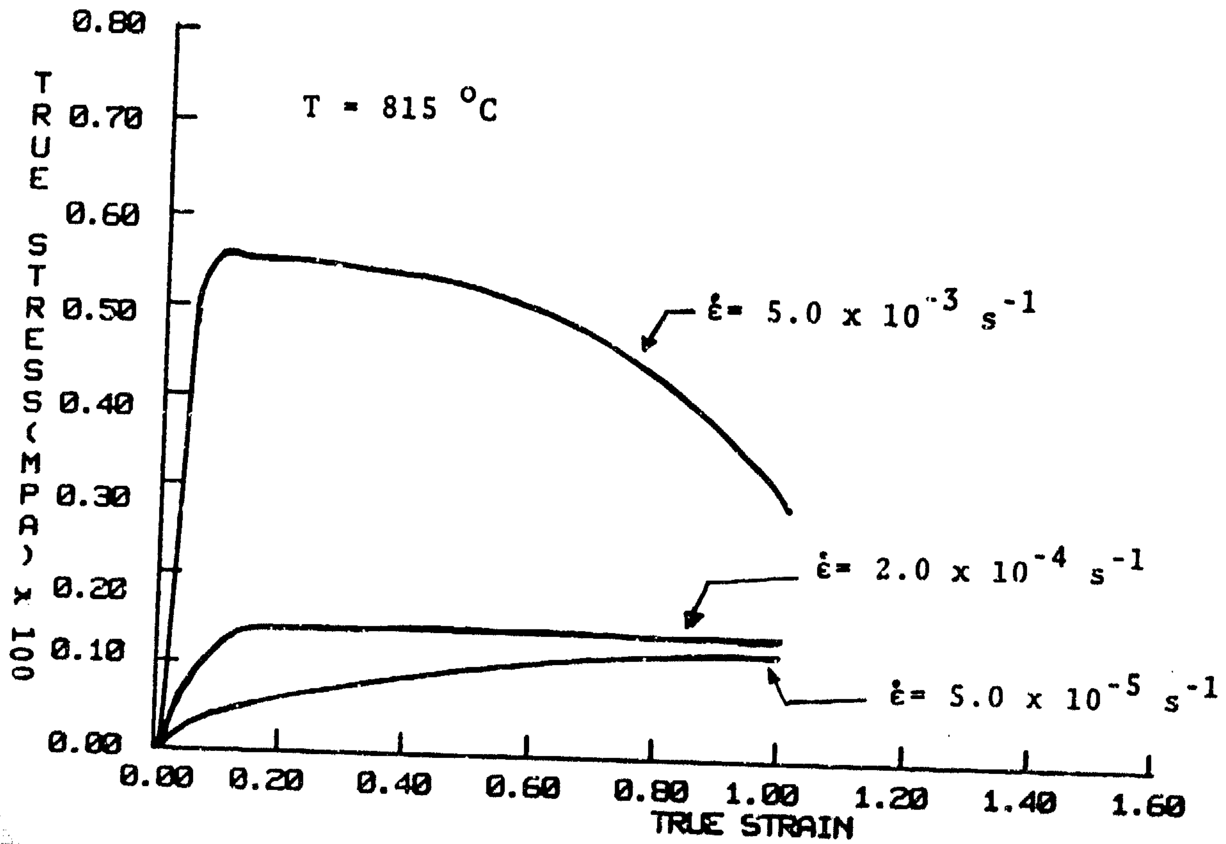

Fig. 1. Effect of strain rate on SPD behavior in Ti-6Al-4V-2Ni at optimum SPF temperature of 815°C and $\epsilon_T = 1.0$.

Fig. 2. Dynamic Recrystallization process associated with strain softening during SPD in Ti-6Al-4V-2Ni, at $T = 815^{\circ}C$, $\dot{\epsilon}_T = 5.0 \times 10^{-3}\ s^{-1}$, $\epsilon_T = 1.0$.

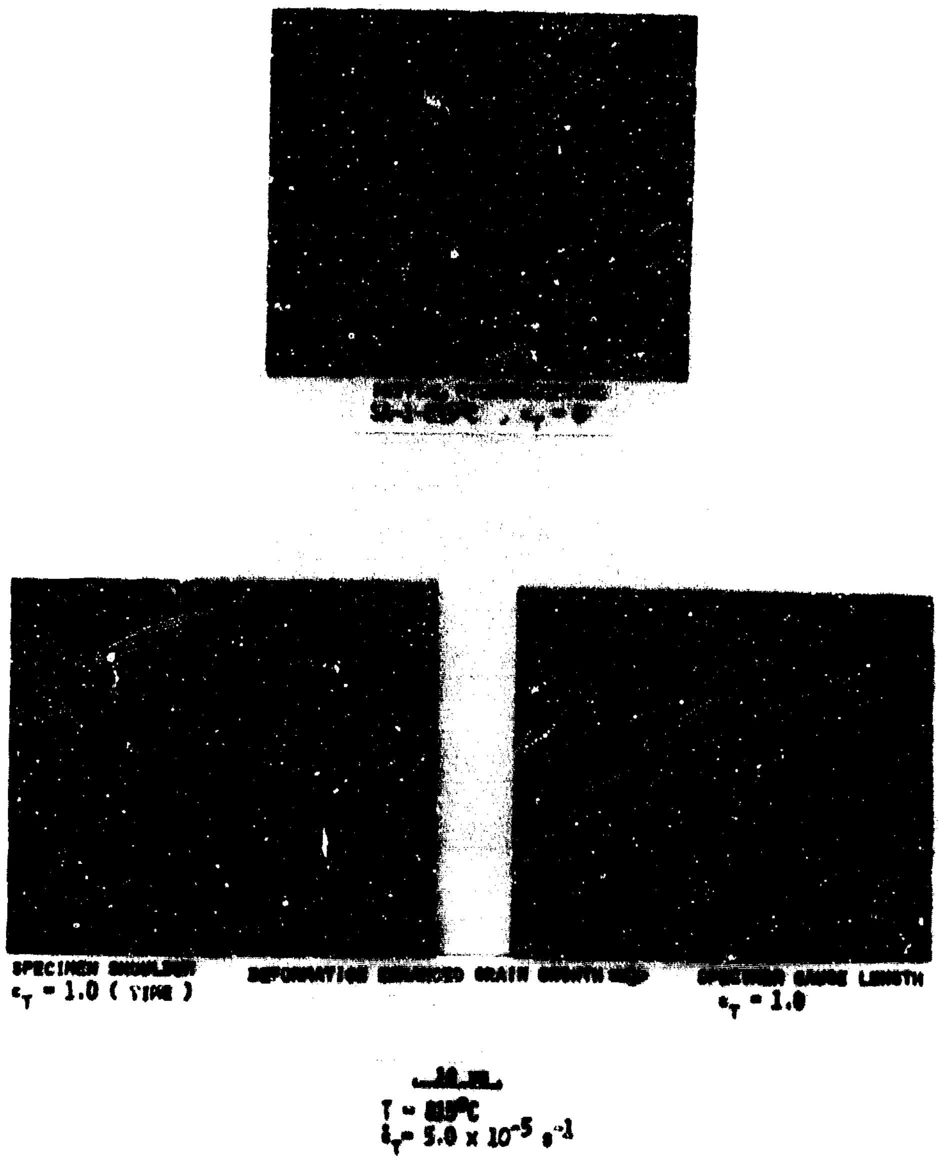

Fig. 3. Deformation enhanced grain growth associated with strain hardening during SPD in Ti-6Al-4V-2Ni at APF temperature (815°), $\dot{\epsilon}_T = 5.0 \times 10^{-5}\ s^{-1}$, $\epsilon_T = 1.0$.

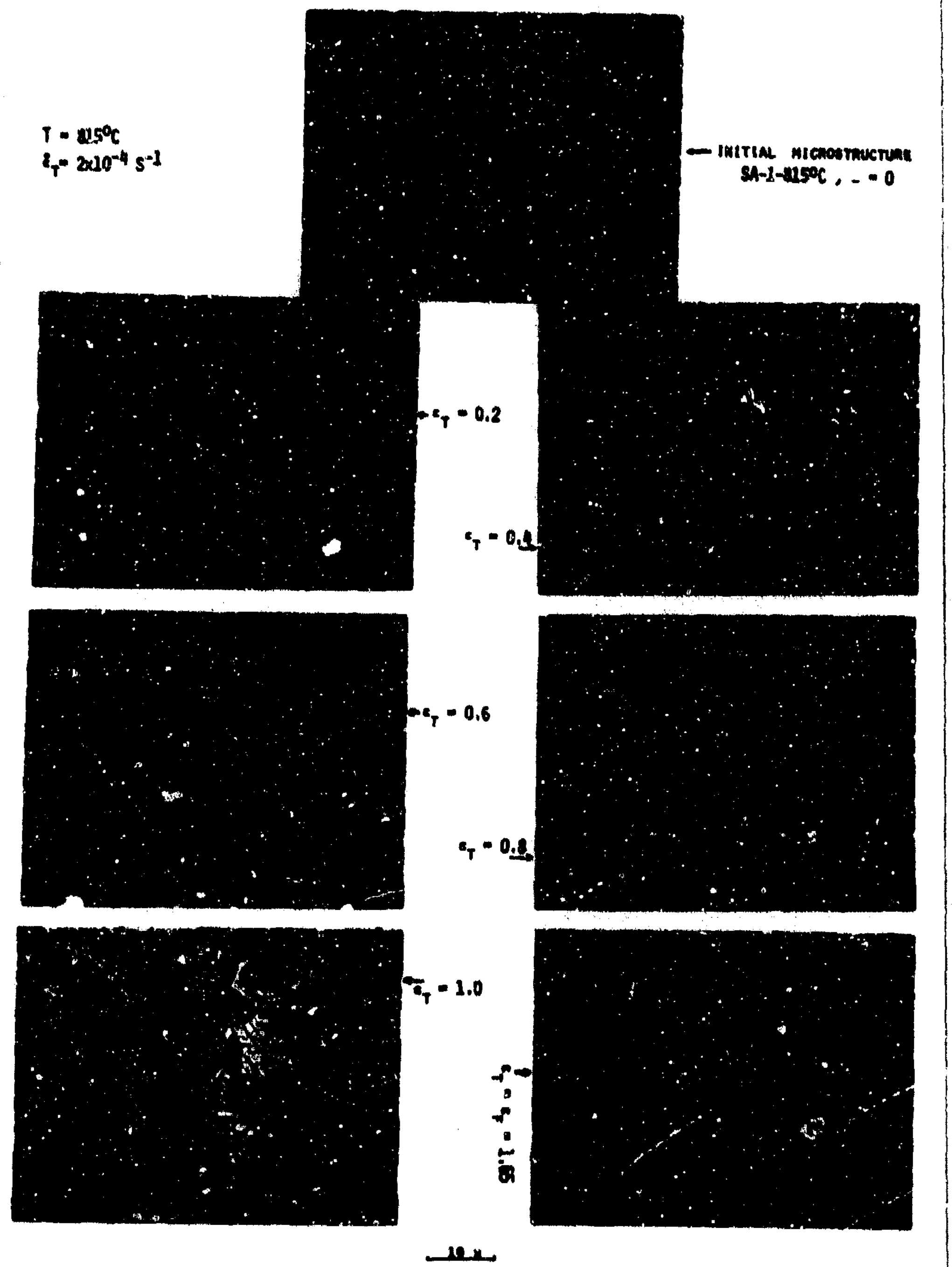

Fig. 4. Microstructural evolution as a function of strain showing the effect of deformation-enhanced phase accommodation in Ti-6Al-4V-2Ni at SPF temperature (815°C) and intermediate strain-rate ($\dot{\varepsilon}_T$ = 2.0 x 10^{-4} s^{-1}).

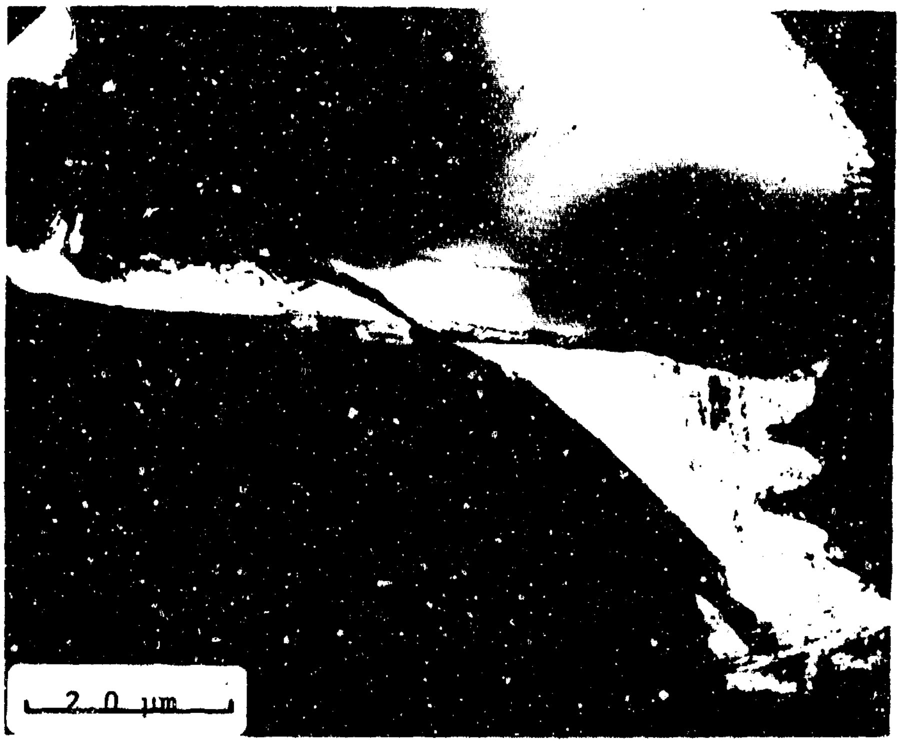

Fig. 5. Accomodation process during SPD in Ti-6Al-4V-2Ni, showing – β-phase injection between two α-phase grains. SA-1-815, $T = 815^\circ C$, $\dot{\epsilon}_T = 2.0 \times 10^{-4}\ s^{-1}$ $\epsilon_T = 0.6$.

LIST OF PUBLICATIONS SPONSORED BY AFOSR

1980 1. LOW STRESS AND SUPERPLASTIC CREEP BEHAVIOR OF Zn-22% Al EUTECTOID ALLOY,
A. Arieli, A. K. S. Yu, and A. K. Mukherjee, Metallurgical Transactions, Vol. 11A, pp. 181-191.

2. FACTORS AFFECTING THE MAXIMUM ATTAINABLE DUCTILITY IN A SUPERPLASTIC TITANIUM ALLOY,
A. Arieli and A. Mukherjee Materials Science and Engineering, Vol. 43, pp. 47-54.

3. HIGH-TEMPERATURE DIFFUSION-CONTROLLED CREEP BEHAVIOR OF THE Zn-22% Al EUTECTOID TESTED IN TORSION,
A. Arieli and A. K. Mukhjerjee, Acta Metallurgica, Vol. 10, pp. 1571-1581.

1981 4. AN EVALUATION OF THE EFFECTS OF CONCURRENT GRAIN GROWTH DURING SUPERPLASTIC FLOW OF THE Ti-6Al-4V ALLOY,
A. Arieli, B. J. MacLean and A. K. Mukherjee, Proc.of the 4th Intnl. Conf.on Titanium, Kyoto, Japan, Ed. H. Kimura and O. Izumi, pp. 1047-1056.

5. TWO- AND THREE-DIMENSIONAL DEFORMATION MECHANISM MAPS FOR HIGH TEMPERATURE CREEP OF Zn-22% Al EUTECTOID ALLOY,
A. Arieli and A. K. Mukherjee, Materials Science and Engineering, Vol. 47, pp. 113-120.

6. REPLY TO "A CRITICAL EVALUATION OF THE CONCEPT OF A UNIVERSAL PARAMETER TO UNIQUELY SPECIFY HIGH TEMPERATURE CREEP MECHANISMS",
A. Arieli and A. K. Mukherjee, Scripta Metallurgica, Vol. 15, Sept. 81, p. 1053.

1982 7. THE EFFECT OF STRAIN AND CONCURRENT GRAIN GROWTH ON THE SUPERPLASTIC BEHAVIOR OF THE Ti-6Al-4V ALLOY,
A. Arieli, B. J. McLean and A. K. Mukherjee, Res Mechanica, Vol. 6, pp. 131-159, 1983.

B-1 (In press)

1. A METALLOGRAPHIC STUDY OF CAVITATION IN Ti-6Al-4V ALLOY,
G. Gurewitz and A. K. Mukherjee, Proceedings of Sixth International Conference on Fracture, New Delhi, India, Pergamon Press 1984.

2. CREEP AND DISLOCATION SUBSTRUCTURE,
L. Bendersky, A. Rosen and A. K. Mukherjee, Invited Review, International Metals Review.

B-3 (In Press continued)

3. THE STRAIN RATE SENSITIVITY VALUES IN SUPERPLASTIC DEFORMATION
G. Gurewitz and A. K. Mukherjee, Materials Science and Engineering.

4. CORRELATION BETWEEN MECHANICAL PROPERTIES AND MICROSTRUCTURE IN A NI-MODIFIED SUPERPLASTIC Ti-6Al-4V ALLOY.
B. Hidalgo-Prada and A. K. Mukherjee, Proceedings of ICSMA-7, Montreal Canada.

5. SUPERPLASTICITY-CORRELATION BETWEEN STRUCTURE AND PROPERTIES
M. Suery and A. K. Mukherjee, BOOK.

B-3 (In Preparation)

1. EVIDENCE OF VISCOUS CREEP IN ALPHA-BRASS
B. Hidalgo-Prada and A. K. Mukherjee, Materials Science and Engineering.

2. INCREMENTAL-DECREMENTAL TESTS
G. Gurewitz and A. K. Mukherjee, Material Science and Engineering.

3. STRUCTURAL/MECHANICAL RELATIONS IN Ti-6AL-4V
G. Gurewitz and A. K. Mukherjee, Scripta Met.

LIST OF DISSERTATIONS

1. Ph.D. Dissertion: "Superplasticity and Cavitation in Ti-6Al-4V Alloy" by Giora Gurewitz (completed in 1984).

2. Ph.D. Dissertation: "Structure-property Correlation in Nickel Modified Ti-6Al-4V Alloy—A Study in Superplasticity" by B. Hidalgo-Prada (in preparation).

3. M.S. Dissertation: "Effect of Dynamic Microstructural Evolution During Superplastic Deformation in Ti-6Al-4V" by M. Meier (in preparation).

LIST OF PERSONNEL INVOLVED IN THE RESEARCH

1.	Prof. Amiya K. Mukherjee:	Principal Investigator
2.	Mr. Benjamin Hidalgo-Prada:	Research Engineer
3.	Mr. Michael Meier:	Research Assistant
4.	Ms. Shara Hinote-Williams	Report and Manuscript preparation

LIST OF COUPLING ACTIVITIES

1. Dr. Amit Ghosh and Dr. Murray Mahoney: North American Rockwell Science Center. Informal interaction on superplasticity of 7475-T6 aluminum alloy and Ti-6Al-4V alloy.

2. Dr. J. Wadsworth: Lockheed Palo Alto Lab; interaction with respect to Al-Cu-Li alloys with Zr additions for superplasticity studies.

3. Dr. S. Shastri: McDonnell Douglas Corporation Aircraft Company Research Lab, St. Louis, MO; informal interaction on effect of alloy addition in modifying the properties of Ti-6Al-4V base alloy.